

## Description

# LOW DENSITY EXPLOSION SUPPRESSING FOAMS

### CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from U.S. Provisional Application Serial No. 60/488,747, filed July 17, 2003.

### BACKGROUND OF THE INVENTION

[0002] The present invention relates to lower density polyurethane foams designed to be installed into a fuel tank to minimize or eliminate the chances for fuel tank explosions due to gunfire, collisions and crashes, electrical ignition, lightning strikes or static discharge.

[0003] Reticulated polyurethane foams have been installed in fuel tanks and containers for gasoline, kerosene and jet fuel powered vehicles to suppress explosions. Reticulated foams have a three-dimensional network of connected strands that define void spaces or pores therebetween. Generally, reticulated foams have void volumes of at least 80%, preferably more than 90%.

[0004] When installed inside a fuel tank, the reticulated foam occupies between about 50% to 100% of the interior tank dimensions. The foam helps to inhibit the rapid and uncontrolled spread of a flame front when a spark is introduced into the fuel mixture. The polyurethane foams are most frequently installed in the fuel tanks of military and racing vehicles, which vehicles are often operated under incendiary or static electric discharge conditions. The foams minimize the danger of fire or explosion resulting from static discharges that build up during fueling, and from sparks generated with ballistic hits, lightning strikes, collisions or crashes.

[0005] Coupled with these advantages are certain disadvantages. First, the reticulated polyurethane foams retain a certain portion of the fuel within the tank that cannot be withdrawn therefrom, thus reducing the amount of fuel that can be used to fuel an engine. Consequently, the usable fuel is reduced by about 4% or more. Second, the reticulated foam adds weight, thus adversely affecting fuel economy. As a result, the known explosion suppressing reticulated polyurethane foams used in military aircraft have not been widely used in commercial aircraft. Commercial aircraft would benefit from explosion suppressing

foams if one or both of these disadvantages could be overcome.

[0006] Higher density explosion suppressing reticulated polyurethane foams are shown in the prior art. U.S. Patent Nos. 4,886,626 (Cope et al.) and 5,028,355 (Cope et al.) describe a conductive reticulated polyurethane foam for use as an explosion suppressing material that contains a charge transfer agent selected from the group consisting of tetracyanoethylene (TCNE), picric acid and analogs of such acid. These foams exhibit volume electrical resistivities of  $10^{12}$  ohm-cm or less. However, the foams have densities from about 1.2 pounds per cubic foot [19.2 kg/m<sup>3</sup>] and higher, and use charge transfer materials that are dangerous to handle. For example, TCNE is highly toxic, and picric acid and its derivatives are explosive.

[0007] U.S. Patent No. 5,567,740 (Free) discloses a conductive reticulated polyurethane foam that includes tetracyanoquinodimethane (TCNQ) as a charge transfer additive to reduce the volume electrical resistivity of the foam. The working examples produced reticulated foams with densities between 1.2 and 1.6 pounds per cubic foot [19.2 and 25.6 kg/m<sup>3</sup>].

## **SUMMARY OF THE INVENTION**

[0008] In a first aspect of the invention, a three dimensional structure for use as an explosion suppressing material in a fuel tank is a reticulated polyurethane foam prepared by (i) reacting at least one polyester or polyether polyol, or a mixture of such polyols, and at least one isocyanate compound under foaming conditions to produce a polyurethane foam having a density less than 1.0 pounds per cubic foot [ $16 \text{ kg/m}^3$ ], and (ii) reticulating said polyurethane foam. The polyurethane foam preferably has a density of from 0.6 to 0.9 pounds per cubic foot [ $9.6$  to  $14.4 \text{ kg/m}^3$ ]. Optionally, the foaming may be carried out under controlled vacuum conditions, such as from 0.6 to 0.95 bar (absolute). Reticulation may be by thermal or chemical reticulating methods.

[0009] One or more antistatic agents optionally may be added to the foam-forming mixture. The resulting polyurethane foam preferably then has a volume electrical resistivity of less than  $10^{12}$  ohm-cm at 70EF [21.1EC].

[0010] In a second aspect of the invention, the three dimensional structure of reticulated polyurethane foam so produced with a density of less than 1.0 pcf [ $16 \text{ kg/m}^3$ ] is installed into an internal volume of a fuel or storage tank in a method for suppressing an explosion in such tank. Prefer-

ably, the foam fills from 50 to 100%, more preferably from 50 to 90% of the inner volume of the tank. Such foam passes flame arrestance test(s) applicable for use in commercial aircraft fuel tanks.

## **DESCRIPTION OF THE FIGURES**

- [0011] FIG.1 is a combined graph showing fuel tank temperature (EK) and pressure (psig) versus time in milliseconds, showing the results of a flame arrestance test before and after an ignition in a fuel tank that does not contain an explosion suppressing foam;
- [0012] FIG. 2 is a combined graph showing fuel tank temperature (EK) and pressure (psig) versus time in milliseconds, showing the results of a flame arrestance test before and after an ignition in a fuel tank that contains a commercially available explosion suppressing foam with a density of 1.3 pounds per cubic foot [ $20.8 \text{ kg/m}^3$ ]; and
- [0013] FIG. 3 is a combined graph showing fuel tank temperature (EK) and pressure (psig) versus time in milliseconds, showing the results of a flame arrestance test before and after an ignition in a fuel tank that contains a low density explosion suppressing foam according to the invention.

## **DETAILED DESCRIPTION**

[0014] In general, polyurethane foams are prepared by reacting a polyol with a polyisocyanate in the presence of a catalyst, a blowing agent, one or more foam stabilizers or surfactants and other foaming aids. The gas generated during polymerization causes foaming of the reaction mixture to form a cellular or foam structure. In the present invention, the polyol preferably is a polyether polyol, although polyether graft polyols and ester polyols may also be used, and the polyether polyols also may be mixed with the polyether graft polyols or ester polyols.

[0015] Polyether polyols used to prepare flexible polyurethane foams typically have molecular weights between 500 and 8000 ( *i.e.* , number average molecular weight measured by gel permeation chromatography). One example of such polyether polyol is Voranol 3010 from Dow Chemical (having a reported molecular weight of about  $3000 \pm 100$ , which is determined by a formula which corresponds well to number average molecular weight measured by gel permeation chromatography), and a hydroxyl number ("OH") of 56 mg KOH/g with an EO content of 8.5%. Another example is Pluracol 1103 from BASF (having a reported molecular weight measured of about 3100 which is determined by a formula which corresponds well to num-

ber average molecular weight measured by gel permeation chromatography). The following paragraph provides a more detailed description of these polyols but is not intended to be limiting.

[0016] The term polyether polyol includes linear and branched polyether (having ether linkages) and containing at least two hydroxyl groups, and includes polyoxypropylene polyether polyol or mixed poly(oxyethylene/oxypropylene) polyether polyol. Preferred polyethers are the poly-oxyalkylene polyols, particularly the linear and branched poly(oxyethylene) glycols, poly(oxypropylene) glycols and their co-polymers.

[0017] Graft or modified polyether polyols are those polyether polyols having a polymer of ethylenically unsaturated monomers dispersed therein. Representative modified polyether polyols include polyoxypropylene polyether polyol into which is dispersed poly(styrene acrylonitrile) or polyurea, and poly(oxyethylene/oxypropylene) polyether polyols into which is dispersed poly(styrene acrylonitrile) or polyurea. Graft or modified polyether polyols contain dispersed polymeric solids. The solids increase hardness and mechanical strength of the resultant foam. Especially preferred graft polyols in this invention are Arcol HS-100

from Bayer AG and Voranol 3943 from Dow. Modified polyether polyols are commercially available from several companies, including Arco, now Bayer (supplied as "Polymer Polyol" or "PHD Polyol"), BASF (supplied as "Graft Polyol"), and Dow Chemical (supplied as "Co-polymer Polyol"). Bayer ("Polymer Polyol"), BASF, and Dow disperse poly(styrene acrylonitrile) into the polyol, whereas Bayer ("PHD Polyol") disperses polyurea therein.

[0018] Ester polyols include polymeric polyols containing a number of ester groups in the main or side chains. Ester polyols are commercially available from Witco Chemical (supplied as "Fomrez 50") and from Inolex (supplied as "1102-50"). 1102-50 is a 50 hydroxyl triol ester polyol with a molecular weight of about 3000.

[0019] The polyol component may comprise a mixture of a polyether graft polyol with an ester polyol, or a mixture of a polyether graft polyol with a polyether polyol, or a mixture of an ester polyol with a polyether polyol.

[0020] The "hydroxyl number" for a polyol is a measure of the amount of reactive groups available for reaction. The value is reported as the number of milligrams of potassium hydroxide equivalent to the hydroxyl groups found in one gram of the sample. "Functionality" of a polyol is

defined as the average number of hydroxyl groups sites per molecule.

[0021] The term "polyisocyanate" refers particularly to isocyanates that have previously been suggested for use in preparing polyurethane foams. Polyisocyanates include di- and poly-isocyanates and prepolymers of polyols and polyisocyanates having excess isocyanate groups available to react with additional polyol. The amount of polyisocyanate employed is frequently expressed by the term "index" which refers to the actual amount of isocyanate required for reaction with all of the active hydrogen-containing compounds present in the reaction mixture multiplied by 100. For most foam applications, the isocyanate index is in the range of between about 75 to 140. In this invention, the preferred isocyanate index is in the range of 100 to 120, most preferably 105 to 115.

[0022] The polyisocyanates include aromatic and aliphatic polyisocyanates each containing at least two isocyanate groups in a molecule, and modified products thereof. Preferably, toluene diisocyanate (TDI) comprises the only polyisocyanate used in the foaming mixture. However, methylene diisocyanate (MDI) can also be used. Commercially available toluene diisocyanates generally constitute

one of the following isomer blends: 80% 2, 4 toluene diisocyanate with 20% 2,6 toluene diisocyanate; or 65% 2,4 toluene diisocyanate with 35% 2,6 toluene diisocyanate. Other higher molecular weight isocyanate oligomers may also be used.

[0023] The methylene diisocyanates suitable for use are diphenyl methane diisocyanate and polymethylene polyphenyl isocyanate blends (hereinafter sometimes referred to as "MDI" or "polymeric MDI"). The MDI blends can contain diphenylmethane 4,4' diisocyanate as well as the 2,2' and 2,4' isomers and higher molecular weight isocyanate oligomers, and have an isocyanate functionality of from about 2.1 – 2.7, preferably from about 2.1 – 2.5. As used herein, the term "isocyanate functionality" means the molar average number of isocyanate groups per molecule of the blends.

[0024] Catalysts are used to control the relative rates of water-polyisocyanate (gas-forming) and polyol-polyisocyanate (gelling) reactions. The catalyst may be a single component or in most cases a mixture of two or more compounds. Preferred catalysts for polyurethane foam production are organotin salts and tertiary amines. The amine catalysts are known to have a greater effect on the water-

polyisocyanate reaction, whereas the organotin catalysts are known to have a greater effect on the polyol-polyisocyanate reaction.

[0025] Catalysts in this invention include amine catalysts, such as triethylene-diamine, imidazoles and tin catalysts, such as stannous octoate. Catalysts are preferably present in amounts from 0.05 to 1.0 parts by weight for amine catalyst, and 0 to 0.5 parts by weight for tin catalyst, based on 100 parts by weight of the polyol component. Other catalysts may be included in the foam-forming mixture, such as gel catalysts often used as replacements for tin catalysts, including zinc octoate or potassium octoate. Preferably, catalysts are incorporated in a pure or concentrated form to avoid introducing carriers or reactive carriers into the foam-forming mixture, which carriers may leave undesirable residuals in the resulting foam structure.

[0026] One or more stabilizers or surfactants are also included in the foam-forming composition. The surfactants lower the bulk surface tension, promote nucleation of bubbles, stabilize the rising cellular structure and emulsify incompatible ingredients. Stabilizers in the present invention include silicone foam stabilizers or surfactants, and may be present in amounts from 0.5 to 2.0 parts by weight,

preferably from 0.5 to 1.0 parts by weight, based on 100 parts by weight of the polyol component.

[0027] A blowing agent may be included in the foam-forming composition. The most typical blowing agent is water, which is added in an amount suitable to achieve a desired foam density. The amount may vary depending upon the operating pressure during foaming. In this invention, water is added as a blowing agent, typically in an amount of 4.0 to 5.0 parts by weight, preferably from 4.7 to 4.9 parts by weight, per 100 parts by weight of the polyol component. Higher amounts may be added if desired. Water is the preferred blowing agent, but auxiliary blowing agents may be introduced into the foam-forming mixture in some circumstances.

[0028] Surface resistivity is the ratio of DC voltage drop per unit length to the surface current per unit width. In effect the surface resistivity is the resistance between two opposite sides of a square and is independent of the size of the square or its dimensional units. Generally, conductive materials have surface resistivity values of less than  $1 \times 10^3$  ohms/square, static dissipative materials have surface resistivity values less than  $1 \times 10^{12}$  ohms/square, and insulative materials have surface resistivity values of greater

than  $1 \times 10^{12}$  ohms/square. Untreated polyurethane foams are most commonly insulative materials with surface resistivities greater than  $1 \times 10^{14}$  ohms/square, and possibly even greater than  $1 \times 10^{17}$  ohms/square. Such surface resistivity classifications are found in ASTM Test method D-257.

[0029] Volume resistivity is the ratio of the DC voltage per unit thickness to the amount of current per unit area passing through a material. Volume resistivity is generally given in ohm-cm.

[0030] Electroconductive or static dissipative polyurethane foams are known and have been produced by various methods, including:

[0031] (a)blending electroconductive carbon (or other metallic) particles with a mixture of

[0032] polyol, isocyanate(s), catalyst(s), water and foaming agent(s) when foaming the

[0033] polyurethane foam to form a conductive or static dissipative foam in situ;

[0034] (b)impregnating a polyurethane foam with a carbon paint or liquid solution

[0035] containing electroconductive carbon (or other metallic) particles; and

[0036] (c)adding ionic anti-static agents to the polyurethane foam-forming mix to form a

[0037] conductive or static dissipative foam in situ.

[0038] In this invention, if anti-static properties are desired, preferably method (c) is employed. Anti-static agents or additives preferably are included in the foam-forming composition in an anti-statically effective amount to cause the resulting polyurethane foam to have a volume resistivity of  $1 \times 10^{15}$  ohm-cm or less at 70EF [21.1EC], more preferably from  $1 \times 10^7$  ohm-cm to  $1 \times 10^{11}$  ohm-cm.

[0039] Representative anti-static agents that may be included in the reaction mixture include quarternary ammonium compounds, including but not limited to quarternary ammonium salts of alkyl sulfuric acid and carboxylic acid; metallic salts of lithium, sodium, potassium, ammonium, calcium, and barium; complexes of metallic salts with polyhydric alcohols and their derivatives, such as 1,4 butanediol, ethylene glycol, propylene glycol and polyethylene glycol, and complexes of metallic salts with mono-ols such as ethylene glycol monomethyl ether and ethylene glyco monoethyl ether; hexahalogenated ionic compounds, including hexahalogenated phosphate compounds, such as potassium hexafluorophosphate, sodium

hexafluorophosphate and ammonium hexafluorophosphate; and carbon black. A commercially available quaternary ammonium compound is Catafor PU by Ace-tochem. Other anti-static agents that may be incorporated include TCNQ, TCNE and picric acid and its analogs, all as disclosed in U.S. Patent Nos. 5,567,740 and 4,886,626. The anti-static agents may be incorporated into the polyol component directly at the mix head or in advance of presenting the polyol to the mix head. The anti-static agents are added in amounts from 0.1 to 20 parts per hundred parts polyol.

[0040] A2020 is a commercially available metallic salt anti-static additive composition offered by ChemFoam. A2020 contains from 4.5 to 5.0% of the active metallic salt that is carried by diglyme (2-methoxyethylether) and triol, and has OH# 48. Other commercially available metallic salts include AT20 by Witco, now Crompton, which contains 5.0% of the active metallic salt carried by diglyme and polyether (OH# 46), and Stature III by Dow Chemical.

[0041] Cross-linking agents may be included in the foam-forming composition to enhance processing and foam stability. Typically, cross-linking agents are relatively small molecules containing 2 or 3 active hydrogen groups,

and are added in amounts from 0 to 25 parts per hundred parts polyol. Representative cross-linking agents that may be included in the reaction mixture include diethanolamine (DEOA), ethylene glycol (EG), diethylene glycol (DEG), triethylene glycol (TEG), propylene glycol (PG), dipropylene glycol (DPG), 1,4 butanediol (BDO), commercially available as Bayer AG DP1022 and R2580.

[0042] Optionally, other additives may be incorporated into the foam-forming composition. The optional additives include, but are not limited to, fire retardants, stabilizers, antimicrobial compounds, extenders, dyes, and pigments. Such additives should not have a detrimental effect on the properties of the final polyurethane foam.

[0043] The polyurethane foams of the present invention may be prepared using the one shot or the pre-polymer methods that are well known to the art, and in which hydroxyl containing ingredients (polyols) and polyisocyanates are combined in the presence of catalysts, blowing agents, foam stabilizers, flame retardants, pigments and extenders. Polyester based polyurethanes, polyether based polyurethanes, copolymer polyol based polyurethanes and mixtures of these substances may be used in making the low density, conductive foams of the present invention.

Polyether polyurethane foams are preferred.

[0044] Once the foam-forming ingredients are mixed together, it is known that the foam may be formed under either elevated or reduced controlled pressure conditions. PCT Published Patent Application WO 93/09934 discloses methods for continuously producing slabs of polyurethane polymers under controlled pressure conditions. The foam-forming mixture of polyol, isocyanate, blowing agent and other additives is introduced continuously onto a moving conveyor in an enclosure with two sub-chambers. The foaming takes place at controlled pressure. Reaction gases are exhausted from the enclosure as necessary to maintain the desired operating pressure. The two sub-chambers, a saw, and air tight doors are operated in a manner that allows for continuous production of slabstock polyurethane foam.

[0045] Most preferably in this invention, the foaming is carried out under controlled vacuum conditions from 0.6 to 0.95 bar (absolute). Alternatively, the lower density foam may be made at atmospheric pressure using auxiliary blowing agents, such as liquid carbon dioxide, pentane or acetone.

[0046] Preferably, the low density foams according to the invention have densities below 1.0 pcf [ $16 \text{ kg/m}^3$ ], most

preferably from 0.6 pcf to 0.9 pcf [(9.6 to 14.4 kg/m<sup>3</sup> ], and cell sizes in the range of 8 to 33 ppi [3.15 to 12.99 pores per cm].

[0047] The foam may then be reticulated, preferably by thermal reticulation such as by introducing the foam into a closed chamber with oxygen and hydrogen gases and igniting the gases to cause an explosion. The explosion or flame breaks the cell membranes, but leaves the cell strands intact. See U.S. Patent No. 3,175,025 (Geen et al.). The foam may also be chemically reticulated, such as by immersing the foam in a caustic solution. Reticulation improves the liquid holding capacity of the foam.

[0048] The reticulated foam is inserted into the inner volume of a fuel storage tank to fill from 50 to 100% of the tank volume, preferably from 50 to 90% of the tank volume. Once wetted with liquid, such as fuel, the foam generally swells to fit more snugly in the tank. The foam may be cut to various shapes to match the internal configuration of the tank. Typically, the foam may be cut or shaped into a series of blocks that may be stacked individually one on the other to fit into the tank and around fuel lines and other internal tank obstructions. The foam blocks optionally may have portions of foam material removed therefrom as

desired to fit into the tank or minimize fuel the amount of foam mass within the tank.

[0049] The foam nests in the tank and is under compression so that it does not substantially move once placed inside the tank. Liquid and gaseous fuel may flow through the pores in the foam, so that the foam does not inhibit fuel delivery to the engine. Due to the liquid wicking characteristic of the reticulated foam, the foam structure will retain a small portion of the fuel therein, commonly up to about 4%. The lower density foams in some cases retain less fuel than the higher density foams previously used in fuel tanks.

[0050] The foam structure has primary use as an explosion suppressing material in tanks for aircraft that store petroleum fuels, such as jet fuel, gasoline and kerosene. The reticulated foam may also be used in fuel tanks and storage tanks for gasohols or alcohol fuels.

[0051] Each aircraft model generally has a different fuel tank design. For example, each tank in a Boeing 737 will hold about 10,000 board foot of foam. At 1.3 pounds per cubic foot [ $20.82 \text{ kg/m}^3$ ] density, this quantity of foam weighs 1083 pounds [491 kg]. If the 1.3 pcf foam were replaced with a lower density foam having a density of 0.8 pounds per cubic foot [ $12.81 \text{ kg/m}^3$ ], the same 10,000 board

foot quantity of foam would weigh 667 pounds [300 kg], thus reducing the foam weight by 38.4%.

[0052] The invention is further illustrated, but not limited by, the following examples.

[0053] **EXAMPLES**

[0054] The components and the amounts used to prepare a static dissipative explosion suppressing polyurethane foam according to the invention is set out below in Example 1. The foam was prepared on a variable pressure foam machine in a manufacturing facility. The foam formulation components were introduced to the mixing head and then poured onto a moving conveyor inside a controlled pressure chamber. The pressure inside the chamber was maintained below 1 atmosphere (absolute). After the foam was allowed to cure for 48 hours, it was thermally reticulated.

[0055] **Example 1 (Inventive Explosion Suppressing Foam)**

[0056]

Component	Description	Parts by Weight
56-16	Ether polyol from Shell	50.0
HL 430	Graft ether polyol from Dow Chemical	50.0
H <sub>2</sub> O		4.7 to 4.9
L618	Silicone surfactant from OSi Specialties	1.0

Stannous octoate	Gel catalyst - available from different suppliers	0.12 to 0.22
ZF 123	Amine catalyst from Huntsman	0.03 to 0.1
TD33A	Amine catalyst from Huntsman	0.03 to 0.1
TD 80	toluene diisocyanate	
Index	Isocyanate index	102 to 115
Pressure	Vacuum condition	600 millibar absolute
Density		0.8 pcf [12.8 kg/m <sup>3</sup> ]
Resistivity		> 1 x 10 <sup>15</sup> ohm-cm

[0057] **Example 2 (Prior Art Explosion Suppressing Foam)**

[0058]

Component	Description	Parts by Weight/ Range
Voranol 3010	Ether polyol from Dow Chemical	50.0
HS 100	Graft ether polyol from Bayer	50.0
H <sub>2</sub> O		4.5 to 4.8
L6202	Silicone surfactant from OSi Specialties	0.8 to 1.2
Stannous octoate	Gel catalyst - available from different suppliers	0.15 to 0.3
C124	Amine catalyst from OSi Specialties	0.3 to 0.8
TD33A	Amine catalyst from Huntsman	0.1 to 0.4
TD 80	Toluene diisocyanate	
Index	Isocyanate Index	105 to 115
Pressure		1 bar
Density		1.3 pcf [20.8 kg/m <sup>3</sup> ]

Resistivity		$> 1 \times 10^{15}$ ohm-cm
-------------	--	-----------------------------

[0059] A flame arrestance test measures the ability of the foam to inhibit flame propagation. The test is performed by placing the explosion suppressing material inside a flame tube apparatus (generally 4" diameter stainless steel tube with length approximately 20" [10.16 cm diameter x 50.8 cm length]). The air in the tube is replaced with a stoichiometric methane/air mixture (4.5 to 5.2 volume percent methane). Pressure and temperature are monitored at each end of the tube, the upstream end on one side of the explosion suppressing material and the downstream end on the other side of the explosion suppressing material. The methane/air mixture is ignited with a spark at the upstream end of the tube. The downstream pressure and temperature measurements are compared to the upstream pressure and temperature measurements. The test was modified from military standard test MIL-PRF-87260A (USAF).

[0060] FIGs. 1 to 3 show graphs of the results of the explosion suppression tests. The graphs compare upstream and downstream temperature (in EK) versus time (in msec), and also show downstream pressure (psig) versus time (msec).

[0061] FIG. 1 shows the result if no explosion suppressing material is inserted into the testing tube apparatus. The upstream temperature (curve 10 ) and downstream temperature (curve 20 ) are at 300 EK before the ignition. Both the downstream temperature (curve 20 ) and pressure (curve 30 ) increased at approximately 200 msec, when the ignition occurred.

[0062] FIG. 2 shows the result for the foam of Example 2, a commercially available higher density explosion suppressing foam from Foamex International Inc. The downstream temperature (curve 20A ) remained at 300 EK after the ignition occurred upstream at about 80 msec. The upstream temperature (curve 10A ) elevated to above 350 EK, which confirms that an ignition took place at 80 msec. The foam was able to stop the flame from propagating downstream. Pressure (curve 30A ) did not elevate significantly after the ignition.

[0063] FIG. 3 shows the result for the foam of Example 1, a lower density foam according to the invention. For this foam also, the downstream temperature (curve 20B ) remained at 300 EK after the ignition occurred upstream (at about 10,000 msec). The upstream temperature (curve 10B ) elevated to above 350 EK, which confirms that an ignition

took place at 10,000 msec, but the downstream temperature (curve 20B ) remained constant. The downstream pressure (curve 30B ) remained nearly constant as well. Thus, the inventive foam also was able to stop the flame from propagating downstream.

[0064] If a foam of 1.3 pcf [ $20.82 \text{ kg/m}^3$ ] is replaced with a lower density foam of 0.8 pcf [ $12.8 \text{ kg/m}^3$ ] with equivalent explosion suppressing capacity, this translates to a weight savings of about 38 to 39%. The aircraft will have greater fuel efficiency, or may be able to take on a greater weight of passengers or cargo. The lower density foam will occupy less space in the fuel tank, that is, it will have more void volume. The extra available space can now be occupied by more fuel.

[0065] The invention has been illustrated by detailed description and examples of the preferred embodiments. Various changes in form and detail will be within the skill of persons skilled in the art. Therefore, the invention must be measured by the claims and not by the description of the examples or the preferred embodiments.